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Tevatron Beam Position Monitor Upgrade Requirements

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Abstract

The Tevatron BPM Upgrade Project will replace the current BPM electronics and the data acquisition system used to transfer information between the BPMs and the Accelerator Controls Systems. As part of the project, the software used to read out, transfer, store, and analyze the BPM data will be upgraded. The goal of the project is to provide a BPM system based on modern hardware and software that gives the higher resolution and expanded functionality necessary to efficiently understand and operate the Tevatron Collider now and for the foreseeable future. Deliverables of the project include all relevant documentation, manuals, users' guides and any other written records necessary for maintaining the system. The project includes replacing the Tevatron BLM system interface hardware and software that is tightly coupled to the BPM system.

As part of the project, this note documents the requirements for the Tevatron Beam Position Monitor (BPM) upgrades. It is meant to provide a complete list of requirements necessary to operate the Tevatron through the end of Collider Run II and beyond and to provide the basis for a technical design of the upgraded BPM system. As work on the BPM system progresses it may be necessary to modify some of the requirements because of technical challenges, trade-offs, and time constraints. In that case the changes to the requirements will be incorporated into future version of this report.

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History of this Document

Versions 1 and 2

Version 1 of the Tevatron BPM upgrade requirements resulted from discussions with the Tevatron department physicists and engineers. The purpose of these discussions was to determine the basic capabilities of the upgraded BPM system needed to meet the physics goals for Collider Run II. To summarize, the upgraded BPM system should perform the functions of the present BPM system but with two major improvements.

The first is an improved resolution of the position measurement. The present system reports a beam position with a least significant bit corresponding to 0.15 mm. The requirement for the upgraded system is a precision of 20 μm. The precision is defined as a 3σ requirement implying that 99.73% of the position measurements should fall within ±20 μm. Secondly, the new system should be capable of measuring the position of the protons or antiproton orbits during collider store conditions with both species of particles present in the Tevatron. It is not necessary to measure both the proton and antiproton orbits simultaneously, but it is necessary to switch between the two types of measurements.

Version 1 of the BPM requirements was presented to an internal Fermilab review committee [1]. Following the internal review, suggestions for changes were incorporated into this document and version 2 of the report was published. Included in Version 2 are requirements for the measurement of beam intensity, addition of a turn-by-turn (TBT) mode, addition of pbar orbit measurements, specifications on the bandwidth of the measurements, and an example of the procedure that is presently used for orbit smoothing. It was also recognized that the Tevatron Beam Loss Monitor (BLM) system was integrated into the existing BPM system and would need consideration.

Version 3

Part of the Collider Run II plan involves upgrading the Tevatron BPM system. This plan currently exists as a project (with WBS number 1.3.4.6.4) within the Run II upgrade plan. For the success of this project it is important that the requirements for the BPM system are clearly documented, especially since a significant fraction of the work is to be accomplished by groups outside of the Tevatron Department. Version 3 of this report is meant to expand on the previous two versions and clarify ambiguities in the requirements. The changes to this document are based on comments made at the July 2003 DOE review [2], requests for clarification from engineers designing the system, and comments from the internal Fermilab review committee [1]. Most important, the requirements come from the needs of running and understanding the Tevatron for high luminosity operations.

Significant changes to Version 3 include:

- Recognition that the current beam position monitor (BPM) and beam loss monitor (BLM) systems share the same data acquisition hardware. Thus a set of requirements for maintaining the BLM system has been added.

- Addition of requirements on the accuracy of the antiproton position measurements.

- A section explaining the bunch spacing used during Collider operations.

- A summary of the currently used applications programs using BPM data and needed for operations of the Tevatron. A requirement of the new system is that the present capabilities of the existing applications programs be maintained.

Introduction

As part of the continuing effort to improve Collider Run II performance, the BPM system is in need of an upgrade to address several deficiencies in the current system. A primary motivation for a new system is increased resolution of the position measurement to improve the Tevatron lattice measurements. Compared to the old system the upgrade will increase the resolution from 150 μm to 20 μm. Replacement of the current system is also motivated by the need for improved reliability. The current BPM system can be difficult to maintain since it uses outdated hardware which is over 20 years old. It is also not clear that the present system will be able to measure the positions of protons in the presence of the higher antiproton intensities that are planned for Collider Run II. Finally, the current system is not capable of measuring the position of the antiproton beam in the presence of protons. Measuring antiproton orbits will become more important as the performance of the Tevatron is pushed during Collider Run II.

The Beam Position Monitor (BPM) system in the Tevatron serves many purposes related to the startup and daily operations of the Tevatron, lattice measurements, and accelerator studies. The design criteria for the upgraded BPM system are based on these uses which are listed below:

- Measuring the closed orbit positions during collider operations.
- TCLK triggered closed orbit data collection for orbit smoothing.
- Maintaining the orbit positions at CDF and D0 during a collider store.
- 1st turn orbit and intensity data for commissioning and diagnostics.
- Multi-turn orbit and intensity data for commissioning.
- 1st turn orbit data and TCLK triggered closed orbit data for injection closure.
- Last turn data for tune up and diagnostics of the A0 beam dump.
- Diagnosing aborts using a circular buffer of closed orbits measurements.
- Archiving orbits during shot setups with the Sequenced Data Acquisition (SDA.)
- Measuring and fast time plotting (FTP) of orbits positions during aperture scans.
- Lattice measurements using the 1-bump technique.
- Lattice and coupling measurements using turn-by-turn (TBT) measurements.
- Closed orbit measurements during accelerator studies.

The BPM system is required to provide these functions under a variety of beam conditions including coalesced and uncoalesced beam, a range of bunch intensities, and for both proton and antiproton beams.

There are also several functions which are not required of the BPM upgrade. These are listed here for clarity or because these features were included in the design of the present BPM system but are now obsolete.

- The Tevatron BPM system will not abort the Tevatron beam if the beam position is outside of some tolerance. The BPM system will not be used as an input to the

Tevatron abort system. (The BLM system however, will remain in use as part of the Tevatron abort.)

- With the present BPM system, the E1 and E2 houses are outfitted with special turn by turn (TBT) hardware which pre-dated the implementation of the ring-wide TBT. This special hardware is no longer needed at the E1 and E2 houses.

With such a variety of uses and beam conditions it is important that the requirements of the upgraded BPM system are clearly stated and documented. That is the purpose of this report. The report begins with some background on the type of measurements required, the bunch structure used in the Tevatron, and the definition of the precision and accuracy requirements. After clearly defining these concepts the requirements of the BPM system are stated for the variety of uses in the list above. Later sections of the report are related to the requirements for application software using the data from the BPM system.

Scope of the Project

The scope of the BPM upgrade includes everything necessary to perform orbit position measurements needed for Tevatron operations. The exception to this rule is the stripline pickups. Most of the stripline pickups are located in the Tevatron quadrupole magnets and are inaccessible without warming up the Tevatron and opening up the magnet interfaces. This makes it infeasible to consider modifying this component of the BPM system. (Broken pickups will be replaced on an individual basis as part of the current maintenance plan.)

The scope of the BPM project does include the processing electronics, hardware, and software for the 232 BPMs currently installed in the Tevatron, cabling from the tunnel hardware to the electronics, interfacing to the existing Beams Division control system, accelerator controls front end and program library support, diagnostics for maintaining and calibrating the new system, and applications programs. In other words, the scope of the project includes everything the end user of the system needs to make use of the beam position measurements during Tevatron operations.

Included in the BPM upgrade is the Tevatron Beam Loss Monitor (BLM) system. The BLM system is currently controlled by the BPM microprocessors and is therefore directly linked to the BPM upgrade project. Upgrades to the new BPM system must not interfere with the use of the current BLM system. The requirements for maintaining the functionality of the BLM system will be covered in another section of this report.

The scope of the BPM project does not include the BPMs in the P1 and A1 injection lines from the Main Injector to the Tevatron.

Measurement Types

There are several basic types of orbit measurements which are required of the Tevatron BPM system. These are the closed-orbit measurement, the single turn measurement, and the turn-by-turn (TBT) measurement. It is not necessary that the BPM system be capable of making all of these types of measurements simultaneously, but the system should be able to switch between the measurement types. When switching between the different types of measurement types it is expected that all of the BPMs will be in the same mode of operation at the same time, although the actual implementation of mode switching may be done on a house-by-house basis. The basic types of measurement are described in the rest of this section.

Closed Orbit Measurement

The purpose of a closed orbit measurement is to determine the average beam position at each BPM location while beam is circulating in the Tevatron. For this measurement precision and accuracy are more important than getting a single pass measurement of the beam position. In fact, the closed orbit measurement should "average" the beam position over a long enough time scale to average out betatron and/or synchrotron oscillations. The averaging or "narrow band" measurements can be used to improve the resolution and accuracy of a closed orbit measurement.

With the upgraded system, the BPMs should be able to switch between two different levels of averaging. The first level should "average" over a long enough time to average out betatron oscillations. The present BPM system accomplishes this by averaging over by averaging over (8, 16, 32, or 64) single turn measurements. The new BPM system should have a similar feature. Secondly, if desired, the BPM system should be capable of switching to a mode which can "average" over the synchrotron oscillations. Since the lowest synchrotron frequency in the Tevatron is ~30 Hz, this means that the closed orbit measurement should effectively be averaged over ~0.3 seconds.

[In the old BPM system the closed orbit measurement is referred to as a SNAPSHOT. In this case the BPM system determined the closed orbit position by averaging over (8, 16, 32, or 64) single turn measurements. This is enough turns to average out the betatron oscillations, but not enough turns to average out the synchrotron oscillations.]

Single Turn Measurement

For the single turn measurement the position of the beam is determined at each BPM location from a single pass of the beam through the BPM stripline. An essential feature of the single turn mode is that the positions at all BPMs are measured on the same revolution of beam. In this case a revolution is defined to begin at the F0 location where beam first enters the Tevatron. Along with measuring the position, the BPM system must also measure the intensity of the beam at each BPM location. As with the position measurement, the single turn intensity measurement is based on a single pass of beam and the intensity measurements must be taken on the same revolution.

The single turn measurement will used only when there are a limited number of protons in the Tevatron and no antiprotons. This can be with either a single coalesced bunch or with a train of 30 uncoalesced bunches. For the purpose of the single turn measurement, we define the measurement to be the position of the uncoalesced bunch or, in the case of uncoalesced beam, the average position of the 30 bunches.

As an example, the single turn measurement is used to determine the orbit on the first revolution of a group of protons that is injected into an empty Tevatron. This implies that a single turn measurement must have a triggered data acquisition with a trigger resolution of a single turn. The triggering requirements are discussed in a later section.

[In the old BPM system the single turn measurement is referred to as a FLASH measurement. Its primary, but not the only, use is for measuring the first turn orbit in the Tevatron.]

Turn By Turn (TBT) Measurement

A TBT measurement is used to collect the orbit position of the beam at each BPM location once every revolution for at least 8092 consecutive revolutions. Like the single turn measurement, each position measurement is determined from a single pass of beam through the stripline. When operating in TBT mode the data collections by the individual BPMs are synchronized so that the first measurement at each BPM is taken from the same revolution of beam. As in the single turn mode, a revolution is defined to begin at the F0 location. It is important for TBT measurements that the orbit positions are collected for every turn and that there are no missing turns or "gaps" in the data. The TBT measurement is made with only protons in the Tevatron and is not required to function with both protons and antiprotons.

The final design of the BPM system might have the ability be able to supply all three types of measurement simultaneously but this in not a requirement for the upgrade. If necessary the measurement types can be prioritized.

- Turn by turn measurements have the highest priority since the TBT data cannot have any missing turns in the data. The TBT mode should have an arming capability and a trigger to start the TBT data collection. Once the TBT data has been collected the BPM system should be available for the other types of measurements. Once the orbit data for a single turn measurement has been collected the BPMs should return to the closed orbit measurement type within 1 msec.

- Single turn measurements have the next highest priority since the measurement of the orbit on a particular revolution is required. Requests for a single turn measurements may interrupt closed orbit measurements, but may not interrupt

TBT measurements. The BPM system should be ready to acquire a single turn measurement within 1 msec of a request to arm for the single turn mode. Once the orbit data for a single turn measurement has been collected the BPMs should return to the closed orbit measurement type within 1 msec.

- The closed orbit measurement has the lowest priority of the measurement types. However, this should be the default mode for the BPM system if TBT or single turn measurements are not requested.

Orbit Data Acquisition

The manner in which orbit data is collected and stored is an important feature of the BPM system. There are several methods of acquiring orbit data including both real time position measurements and triggered data acquisition. Along with the triggered data acquisition the BPM system should have arming capabilities to prepare for a particular measurement. The orbit measurement data must also be accessible in a number of different formats including ACNET variables and circular buffers. Not all of these options apply to all types of measurements. This section describes the options mentioned and later sections give the data acquisition options required for each type of measurement.

Methods of Data Acquisition

The methods of data acquisition are:

- The collection of an orbit measurement
    - on a manual request
    - on a TCLK event trigger
    - on a State Device transition.

- The real time position at each BPM
    - as an ACNET variable
    - as a fast time plot (FTP) device.

- Automatic periodic orbit measurements for input into a circular buffer.

The upgraded BPM system is required to collect orbit data on a triggered basis and store the data for later retrieval by an applications program. The concept of buffers for storing orbit data is part of the current BPM system and is useful in helping to define the capabilities of the upgraded BPM system. The buffers can be of three types: a single collection of orbit data, a linear buffer which stores sequentially collected orbit data, or a continuously updated circular buffer. A list of the kinds of buffers needed for Tevatron operations includes:

- Single closed orbit measurement collected and stored in a buffer when triggered by a clock event or state device transition.
- A series of closed orbit measurements collected in a linear buffer. When triggered by a TCLK event or state device transition, the BPM system collects an orbit measurement, stores the data in a frame of the buffer, and then advances to the next frame.
- Closed orbit measurements collected periodically and automatically and stored in a circular buffer. The buffer "wraps around" and continues to collect data until it is halted by a TCLK event, a state device transition, or an abort event on the Tevatron abort link. The buffer will not start collecting data again until the BPMs receive a request to restart the buffer.
- A buffer containing the orbit position data that is collected when a TBT measurement is made.

The combinations of measurement types, data acquisition modes, and orbit buffers that are necessary are described in the following paragraphs. Figure 1 shows a sketch of the data acquisition types and buffers for the case of closed orbit measurements.

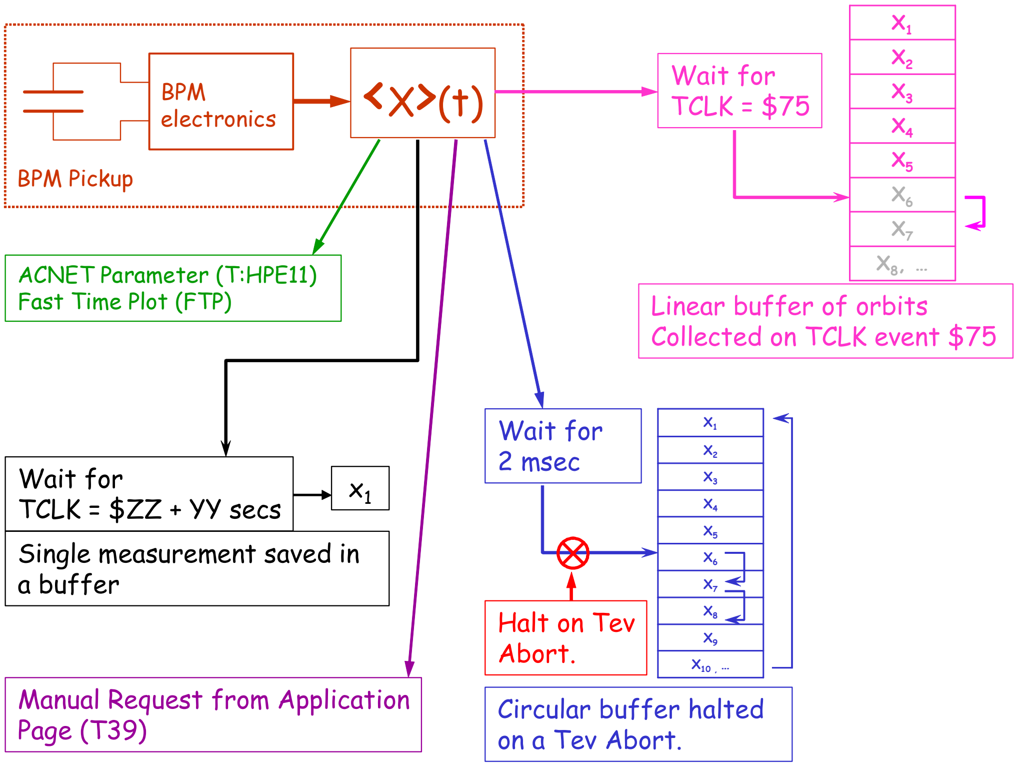

Figure 1 Schematic of the types of buffers for data storage and the types of data acquisition methods needed for the Tevatron BPM system. Shown is a sketch of the modes when the BPM system is in closed orbit mode. The BPM electronics will produce a position measurements <X> which can be read out and stored several different ways. This includes as an ACNET parameter available for fast time plotting (green), as a single measurement stored in a buffer when triggered by a TCLK event (black), a measurement available from an applications program (purple), a circular buffer which is halted on a Tevatron abort (blue), and a linear buffer which collects a position measurements on a TCLK event, saves the measurement in a buffer, and then advances to the next position in the buffer (pink.)

The single turn data and the closed orbit data can be collected by a manual (or software) request for orbit information. Examples of this are a closed orbit measurement requested by an applications program, a call to a controls library routine, or a request from SDA. When an orbit is requested in this manner the BPM system will be polled and return a measurement of the orbit positions. (An example of this in the old BPM system is requesting a SNAPSHOT measurement from T39.)

When operating in closed orbit mode the BPM position at each locations should be available as an ACNET device, such as T:HPE11, with an update rate of 1 HZ. This same device should have fast time plot (FTP) capability at a rate of 720 Hz.

When operating in closed orbit mode the BPM system should periodically save the orbit data in a circular buffer. Orbit data should continually be copied into the buffer as long as there is beam in the Tevatron. The circular buffer should halt when the Tevatron abort link asserts a Tevatron abort. The data should remain in the buffer until the BPM system receives a buffer restart event. The circular buffer should contain 1024 orbits and with a time of 2 msec between each frame in the buffer. (This is similar to the SNAPSHOT abort buffer in the old BPM system.) In addition to this circular buffer, there should also be a second circular buffer which contains 1024 orbits but with a time of 1 second between each measurement.

The BPM system should have a linear buffer which saves a closed orbit into successive frames of the buffer when a specific TCLK event is detected. The buffer should have 128 frames of orbit data and the data should remain in the buffer until the BPM system receives a signal to restart the buffer. (This is similar to the PROFILE data saved in the present BPM system when a $75 TCLK event is detected. The PROFILE data is reset when the BPM detects a “prepare for beam” TCLK event $71.)

There should be a set of single frame buffers each which can store a single closed orbit measurement upon detection of a specific clock event. The TCLK event and the delay from the TCLK event should be settable. (This is similar to the DISPLAY measurement of the current BPM system.)

There should be a set of single frame buffers each which can store single turn measurements upon detection of a specific TCLK clock event. The TCLK event and the delay from the TCLK event should be settable. (This is similar to the FLASH measurement of the current BPM system.)

When operating in TBT mode the measured position of the beam at each turn should be stored in a buffer for later retrieval. The collection of the TBT data should be triggered by a TCLK event. (This is similar to the TBT measurement in the current BPM system.)

Information Contained in the Orbit Frame Data.

Whenever a set of orbit data is collected it should include information in addition to the position measurements.

Some of the items in the orbit frame are related to the mode of the BPM operation and will be the same for all of the BPMs in the same house. These consist of

- Status or Error Code
- BPM Azimuthal Position
- Trigger Settings
- Closed Orbit/Flash Mode Setting
- Proton/Pbar Setting
- Size of Data Array
- Trigger Event for Current Data Acquisition
- Arm Event for Current Data Acquisition

There will also be an array of data that is associated with each individual BPM detector. These include:

- Array of:
  - Status or Error Code
  - Position readings
  - Intensity readings
  - Time stamps

The resolution of the time stamp depends on the type of measurement being made. For single turn measurements or TBT measurements the time stamps are more precise than in the closed orbit mode. In this case, the time stamp data should consist of a time of day that is accurate to within 500 μs and a relative time stamp which can be used to differentiate individual turns in the TBT measurement (i.e. a turn number.)

Beam structure

A requirement for the upgraded BPM system is the ability to measure orbit positions under a variety of beam conditions including coalesced and uncoalesced beam and protons and pbars. Therefore understanding the structure of the beam is an important part of specifying and designing the upgraded BPM system. This section defines the beam structures that are currently used in the Tevatron and those expected for the duration of Collider Run II. This includes the expected beam intensities.

Before defining the bunch structures it is useful to introduce the concept of the RF bucket and its relation to the bunch spacing. Protons circulate in the Tevatron in bunches which are formed by the RF cavities and in principle there could be 1113 equally spaced bunches. In practice the number of bunches is fewer than 1113, they are not equally spaced, and the pattern of the bunches depends on the mode of operation.

The proton bunches circulate around the Tevatron at nearly the speed of light. This means that a single bunch will travel once around the Tevatron in about 20.94 μsec or, equivalently, has a revolution frequency of about 47.74 kHz. While circulating in the Tevatron the proton bunches are contained in RF buckets formed by the electric fields of the RF cavities. The number 1113 is a function of the 1 km radius of the Tevatron and the 53.14 MHz resonant frequency of the RF cavities. The revolution frequency and RF frequency vary slightly as the Tevatron is ramped in energy from 150 GeV to 980 GeV.

In all situations the RF frequency in the Tevatron is exactly 1113 times the revolution frequency. This means that there are 1113 buckets which could potentially be filled with beam. In addition to generating the 53.14 MHz signal supplied to the RF cavities, the Tevatron Low Level RF system (LLRF) also generates a beam sync marker once every 1113 RF cycles. The RF system also creates 1113 buckets for the antiprotons which circulate in the opposite direction of the protons. The LLRF system also generates a beam sync maker associated with the antiproton bunches. The proton and antiproton markers are broadcast over the Tevatron beam sync clock system and are essential for timing information and for enumerating the RF buckets and the bunches.

The relative timing of the proton bunches with respect to the proton beam sync marker is determined by the Tevatron Low Level RF system (LLRF) and the proton bunches are always injected into the Tevatron with the same relative timing. The absolute timing between the protons and beam sync varies as a function of the BPM in the Tevatron ring and the propagation time of the beam sync signal. Therefore the proton beam will arrive at different times (with respect to the beam sync marker) at different BPMs. The same is true for the relative timing of the antiproton bunches and the antiproton beam sync marker. The relative timing of the proton and antiproton bunches changes during Tevatron operations with a process known as cogging.

Uncoalesced Protons

When operating with uncoalesced protons, the Tevatron is injected with ~20 to 30 proton bunches in consecutive RF buckets. This means that there is a batch of ~20 to 30 protons spaced 18.8 nsec apart and then a gap with no beam for about 20.4 μsec. In this case the bunches are approximately Gaussian shaped with a bunch length of 3σ in the range of 3.5 to 10 nsec. In this mode of operations there are no antiproton bunches or additional proton bunches in the Tevatron. The structure and spacing of the protons in uncoalesced mode is shown in Figure 2.

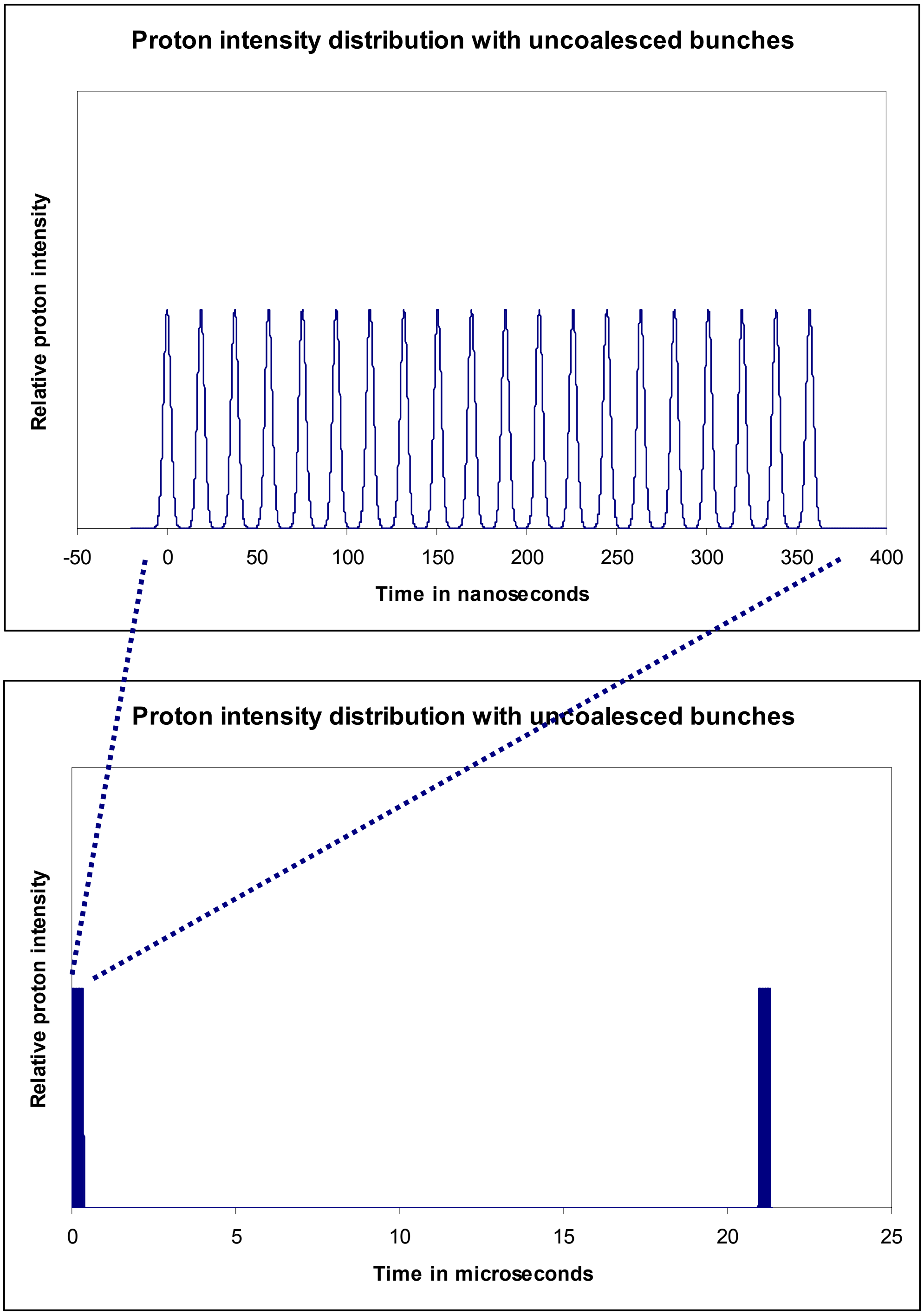

Figure 2 Bunch structure with uncoalesced protons in the Tevatron. There is a group of 20 to 30 consecutive bunches spaced one RF bucket (18.8 nsec) apart followed by a gap of ~20 μsec without beam before the group returns after one revolution. The lower figure shows the beam over a little more than one revolution and the upper figure zooms in on the consecutive bunches.

Coalesced Protons

Coalesced proton bunches are injected into the Tevatron one bunch at a time and there may be up to a total of 36 coalesced proton bunches in the Tevatron. Unlike the uncoalesced case, the coalesced bunches do not occupy consecutive RF buckets but are loaded into a pattern of 36 bunches. The pattern consists of 3 groups of 12 proton bunches with the 3 groups spaced equally apart. Within each group of 12 the coalesced protons are spaced 21 RF buckets (or about 396 nsec) apart. See Figure 3 for a plot of the proton bunch spacing. In the case of coalesced protons, the length of the bunches is typically longer than in the uncoalesced case and the 3σ length is in the range of 4.5 to 10 nsec. As in the coalesced case, the protons are injected into the Tevatron with the same relative timing with respect to the proton beam sync markers.

Coalesced Anitprotons

Occasionally a store or study will be performed with only antiprotons in the Tevatron. The antiprotons are injected into the Tevatron in groups of 4 bunches at a time and therefore an antiproton store will have between 4 and 36 bunches of antiprotons. The bunch structure for the antiprotons is the same as for the protons, but of course the antiprotons travel in the opposite direction of the protons.

Coalesced Protons and Antiprotons

When loading the Tevatron with protons and antiprotons both species of particles are injected as coalesced bunches. The protons are loaded as described in the previous section. The antiprotons are then loaded into the Tevatron in groups of 4 bunches at time until there are a total of 36 coalesced antiproton bunches. The bunch spacing for the antiprotons is the same as for the protons except that the antiprotons are circulating in the opposite direction.

The timing of the proton bunches with respect to the proton beam sync marker is the same as described in the coalesced proton case. There is also an antiproton beam sync marker associated with the antiproton bunches. The antiprotons are always injected into the Tevatron with the same relative timing with respect to the antiproton beam sync marker.

However, the relative timing between the proton and antiproton bunches is change by the process of cogging as the antiprotons are injected. This set of timing is referred to as the injection cogging. During a collider store, the cogging is adjusted so that the proton and antiproton bunches collide at CDF and D0. This timing is referred to as collision point cogging. This has implications for the BPM system since both proton and antiproton bunches can pass through a BPM pickup at nearly the same time. Figure 3 shows the bunch pattern in the Tevatron during a store. Once the protons and antiprotons are in collisions proton bunch 1 (P1) and antiproton bunch 1 (A1) will cross at F0 at the same time.

With the 36x36 bunch structure there are total of 138 locations in the Tevatron where a proton bunch and an antiproton bunch pass by each other. Figure 4 shows a sample section of the Tevatron with a plot of the horizontal and vertical BPM locations and the locations of bunch crossings when the Tevatron is at the collision point cogging. As can be seen from this plot many BPMs are located within about 1 RF bucket of a bunch crossing point. During injection the relative timing of the protons and antiprotons is different since the beams are cogged for injection. This means that the locations of proton and antiproton crossings are different at injection than they are at collisions.

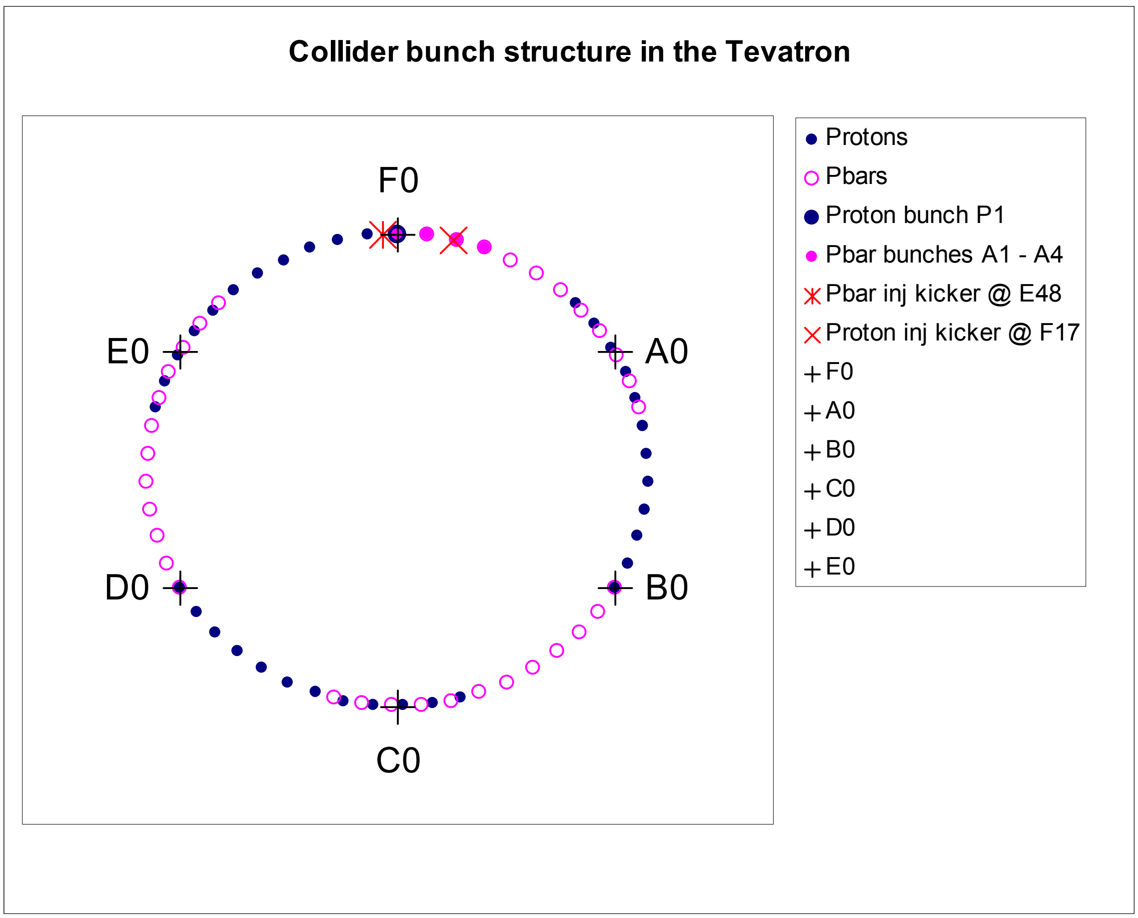

Figure 3 Pattern of proton and antiproton bunches in the Tevatron during a collider store. The proton bunches circulate in the clockwise direction and the antiprotons circulate in the counter-clockwise direction. In this plot the bunches are in the collision point cogging.

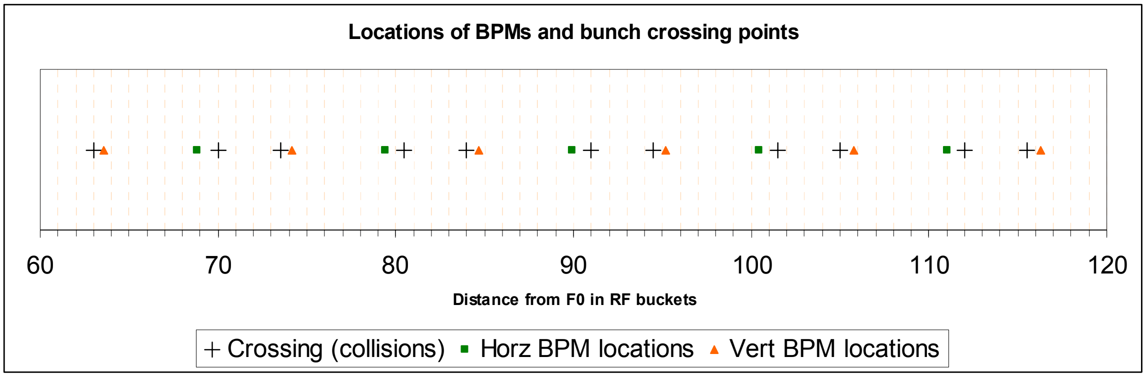

Figure 4 Plot of the location of horizontal and vertical BPMs and the locations of proton and antiproton bunch crossings for a selected portion of the Tevatron ring. This plot shows the crossing locations for the collision cogging.

Beam Intensities and Bunch Lengths

The BPM system is required to handle a range of beam intensity and the bunch length in which depends on the type of operation being performed. In Table 1 the range of intensities and bunch lengths expected in Collider Run II are presented [3].

Table 1: Range of intensities and bunch lengths expected in Collider Run II.

	Particles/bunch	Number of bunches	Bunch length (3σ value in nsec)
Uncoalesced Protons	3e9 to 30e9	30	3.5 to 10
Coalesced Protons	30e9 to 350e9	1 to 36	4.5 to 10
Coalesced Antiprotons	3e9 to 150e9	1 to 36	4.5 to 10

When operating with coalesced protons or antiprotons the number of bunches can vary anywhere between 1 and 36 and the BPM system must be able to make a position measurement with any number of bunches in the Tevatron. It is possible for instance that a store would be done with 36 proton bunches, but only 4 antiproton bunches.

Helical Orbits

In addition to the longitudinal bunch structure, the Tevatron uses electrostatic separators to create separate proton and antiproton closed orbits. These orbits follow a helical pattern about the center of the Tevatron aperture and this creates a transverse separation of the proton and antiproton bunches. In the Tevatron the largest separations are when the Tevatron is at 150 Gev where the protons and antiprotons can be separated by as much as 20 mm. The transverse separation between the protons and antiprotons varies as a function of position around the Tevatron so that each BPM can have a different relative position of the proton and antiproton beam. In addition, the configuration of the helix changes during the shot setup process and the beam separations are different at 150 Gev during injection than they are when the Tevatron is at low beta during a store.

Position Measurement Specifications

Definition of terms

The **measurement range** is defined as the range of positions, relative to the BPM center, over which the BPM measurement must be valid and meet the accuracy requirements. For the upgrade, the BPM system must report accurate beam positions over a range of ±15 mm from the center. For beam positions beyond this range there are no specific requirements on the accuracy of the beam position, but it is desirable if the BPMs could still read out a position in order to determine which side of the aperture the orbit position is located.

The **absolute position accuracy** of the BPMs determines how well the position of the beam is measured with respect to the center of the quadrupole magnets or with respect to the survey center-line in the warm straight sections. Defining this requirement is difficult since information on the measured mechanical offsets and survey errors is needed to determine an absolute position. For the purpose of the BPM requirements the uncertainties in the mechanical position of the stripline are not considered.

Instead it is assumed that each BPM stripline has a known mechanical offset and, in order to improve accuracy, each BPM measurement should correct for known mechanical offset. For those BPM striplines inside quadrupole magnets, the electrical center of stripline with respect to the center of the quadrupole field was determined at the time of the magnet manufacturing [4]. Corrections for these offsets should be made by each individual BPM before the position measurement is reported.

The **absolute position accuracy** does determine how accurately the BPM system measures the position of the beam for all beam conditions, for the entire range of positions, for long periods of time (years), and when parts of the BPM system or BPM electronics are replaced. It is sufficient for the BPM system to have a 3σ absolute position accuracy of 1 mm.

The **long term position stability** is a requirement on the BPM system's ability to give the same position value for the same beam position and intensity over multiple stores or even a one week shutdown. Essentially this requirement limits the amount of drift allowed by a BPM over the period of a week. The requirement on the long term positions stability is a 3σ drift of 0.05 mm per week.

The **position linearity** is a requirement on the linearity of the BPM response to orbit changes over the measurement range. The linearity is defined as the difference between the measured BPM position and the slope of the BPM response at the center of the BPM. The definition of the position linearity is that the BPM measurement should not deviate by more than 1.5% from the slope of the BPM measurement in the center of the BPM. If Δx_a is then change in the actual position of the beam and Δx_m is the measured position change of the beam, then the measured change $\Delta x_m = \Delta x_a \times (dx_m/dx_a)_{x=0} \pm 1.5\%$. The 1.5% is a 3σ criterion. Note that this requirement is on the linearity of the BPM but not on the accuracy of the BPM measurement scale $(dx_m/dx_a)_{x=0}$. In Figure 5 is a sketch of the linearity requirement.

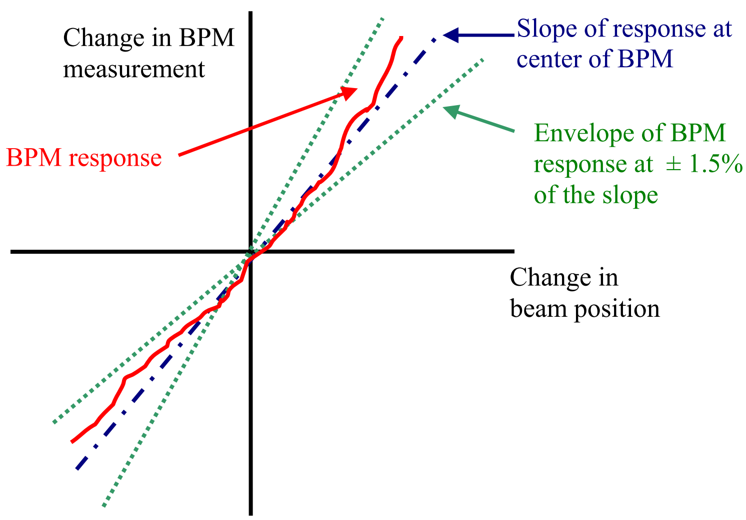

Figure 5 Definition of the linearity requirement for the Tevatron BPM. Note that the requirement on the linearity of the BPM response does not constrain the slope of the BPM response.

The **relative position accuracy** of the BPMs determines how well the displacement of the beam is measured with respect to the actual displacement of the beam over the measurement range. This requirement does not include offset errors, but does set limits on the scale errors, non-linearities, and random errors. For the Tevatron BPMs the relative position accuracy should be 5%. The 5% is a 3σ criterion. In other words, if Δx_a is then change in the actual position of the beam and Δx_m is the measured position change of the beam, then the measured change $\Delta x_m = \Delta x_a \pm 5\%$. When combined, the linearity requirement and the relative position accuracy requirement essentially become a requirement on the accuracy of the slope of the BPM response to position changes.

In addition to the relative position accuracy, it is required that all of the BPMs have the same gain response to within 1.5%. Thus there can be an overall error in the gain of the BPMs, but this should be a systematic error that is the same for all of the detectors.

The **orbit position resolution** is a requirement on the smallest change in beam position that the BPM system can reliably measure. This specification will not be affected by offset errors, but it will be affected by scale errors, non-linearities, and random errors. For the most precise measurements the orbit position precision is given as a 3σ requirement of 20 μm. This means that 99.73% of measurements should fall within ±20 μm is the beam position is not changed. The requirement on the precision is dependent on the operating conditions of the Tevatron. More details on this is given in later sections of this report.

The requirement for **intensity stability** determines how much the orbit measurement can change over the range of beam intensities expected in the Tevatron. The requirement for the Tev BPMs is that changes in the intensity do not change the measured orbit position by more than 2%.

Summary of Accuracy Requirements

Below is a summary of the requirements on the accuracy of the Tevatron BPMs for protons and for antiprotons. The listed requirements are the most stringent requirements. Some of these requirements are relaxed in for some beam conditions and the details are discussed below.

Table 2 Accuracy requirements for the Tevatron BPMs. This table gives the most stringent requirements on the system. For certain types of operation these requirements are relaxed. (See text for more details.)

Key Specifications (Protons): Measurement Range: ±15mm Absolute Position Accuracy: < 1.0 mm Long Term Position Stability: < 0.02 mm Best Orbit Position Resolution: < 0.02mm Position Linearity: < 1.5% Relative Position Accuracy: < 5% Intensity Stability: < 2%
Key Specifications (Pbars) : Measurement Range: ±15mm Absolute Position Accuracy: < 1.0 mm Long Term Position Stability: < 0.02 mm Best Orbit Position Resolution: < 0.05mm Position Linearity: < 1.5% Relative Position Accuracy: < 5% Intensity Stability: < 2%

Requirements of BPMs for Tevatron Operations

This section defines the requirements for the Tevatron BPM system for each of the uses needed to operate the Tevatron.

The design criteria for the upgraded BPM system are based on these uses which are listed below:

- Measuring the closed orbit positions during collider operations.
- TCLK triggered closed orbit data collection for orbit smoothing.
- Maintaining the orbit positions at CDF and D0 during a collider store.
- 1st turn orbit and intensity data for commissioning and diagnostics.
- Multi-turn orbit and intensity data for commissioning.
- 1st turn orbit data and TCLK triggered closed orbit data for injection closure.
- Last turn data for tune up and diagnostics of the A0 beam dump.
- Diagnosing aborts using a circular buffer of closed orbits measurements.
- Archiving orbits during shot setups with the Sequenced Data Acquisition (SDA.)
- Measuring and fast time plotting (FTP) of orbits positions during aperture scans.
- Lattice measurements using the 1-bump technique.
- Lattice and coupling measurements using turn-by-turn (TBT) measurements.
- Closed orbit measurements during accelerator studies.

These are summarized in Table 3 after describing the different uses in paragraph form.

Standard Store:

Closed orbit measurements are made during a collider store in order to monitor the orbit and are used as input for orbit smoothing. During a Collider store the Tevatron is loaded with 36 coalesced proton bunches and 36 coalesced antiproton bunches and the structure of the beam is shown in Figure 3. The intensity of the coalesced proton bunches is near the maximum of 350e9 per bunch and the intensity of the antiproton bunches can be anywhere in the range of 3e9 to 150e9 as listed in Table 1. The accuracy requirements for this type of measurements have the tightest requirements on accuracy and are the same as those listed in Table 2.

Orbits during a Collider Shot Setup:

Closed orbit measurements are collected at various times during a collider shot setup process. This includes TCLK triggered data acquisition of the orbits that are saved into a buffer during the energy ramp and the low beta squeeze. During a Collider store the Tevatron is loaded with 36 coalesced proton bunches and 36 coalesced antiproton bunches and the structure of the beam is shown in Figure 3. The intensity of the coalesced proton bunches is near the maximum of 350e9 per bunch and the intensity of the antiproton bunches can be anywhere in the range of 3e9 to 150e9 as listed in Table 1. The accuracy requirements for the closed orbit measurement are relaxed from those in

Table 2. The resolution of the measurement is required to be only 0.05 mm for the proton position and 0.05 mm for the antiproton position.

Injection Commissioning:

When starting up the Tevatron after a shutdown it is often necessary to retune the injection line and the orbits in the Tevatron. To minimize the chance of quenching it is preferable to use the smallest amount of beam. For this purpose the Tevatron uses uncoalesced beam with intensity near 3e9 per bunch which is near the minimum listed in Table 1. The commissioning of the Tevatron injection relies on both the single turn measurement and the closed orbit measurement and both measurements should be acquired on a TCLK trigger. The requirements on the BPM accuracy for this purpose can be relaxed compared the values listed in Table 2. The closed orbit resolution should be 0.05 mm and the single turn resolution should be 0.1 mm. It is also required that the intensity be measured along with the orbit data for the single turn measurements.

Injection Tune Up:

The requirements for injection tune up are essentially the same as for injection commissioning except that the intensity of the proton bunches will be larger. For injection tune up uncoalesced protons are used with intensity of 30e9 per bunch. The closed orbit resolution should be 0.05 mm and the single turn resolution should be 0.1 mm

Lattice Function Measurement:

Lattice function measurements using the 1-bump method are made in the Tevatron during accelerator study periods using proton only stores. There are no antiprotons in the Tevatron for these measurements. The primary requirement for making lattice function measurements is the collection of precise and accurate differences in closed orbit positions when a change in introduced in one of the trim dipole correctors. The lattice function measurements are made with uncoalesced protons in the Tevatron with 30 bunches and 30E9 per bunch in the Tevatron. This type of measurement has the tightest requirements on the accuracy and are the same as those as listed Table 2.

Pbar Only Store:

There will be certain study conditions that will require pbar only stores in the Tevatron. The BPMs should be able to verify pbar orbits in this condition if at a lower accuracy than the standard configurations. The closed orbit resolution should be 0.05 mm.

Table 3 Summary of the modes of Tevatron BPM operation and the requirements of the system for each mode.

Measurement Purpose	Measurement type	Beam Structure	Data Acquisition Type	Position accuracy and resolution
Protons during a store.	Closed Orbit	36x36.	Manual. Buffered on TCLK. ACNET variable. FTP variable.	As in Table 2
Pbars during a store.	Closed Orbit	36x36.	Manual. Buffered on TCLK. ACNET variable. FTP variable.	Position resolution of 0.05 mm.
Protons during ramp and LB squeeze	Closed Orbit	36x36. Prot coal. Prot uncoal.	Buffered on TCLK. ACNET variable. FTP variable.	Position resolution of 0.05 mm.
Pbar during ramp and LB squeeze	Closed Orbit	36x36. Pbar coal.	Buffered on TCLK. ACNET variable. FTP variable.	Position resolution of 0.05 mm.
Injection commissioning.	Single Turn	Prot uncoal.	Single turn, triggered on TCLK.	Position resolution of 0.1 mm.
Injection commissioning.	Closed Orbit	Prot uncoal.	Buffered on TCLK	Position resolution of 0.05 mm.
Injection tune up.	Single Turn	Prot uncoal.	Single turn, triggered on TCLK.	Position resolution of 0.05 mm.
Injection tune up.	Closed Orbit	Prot uncoal.	Buffered on TCLK.	Position resolution of 0.02 mm.
Closed orbit circular buffer.	Closed Orbit	36x36. Prot coal. Prot uncoal. Pbar coal.	Circular buffer halted on Tevatron Abort.	As in Table 2
Aperture scans	Closed Orbit	Prot coal. Prot uncoal.	Manual. Buffered on TCLK. ACNET variable. FTP variable.	As in Table 2
Lattice measurements	Closed Orbit	Prot uncoal. Prot coal.	Manual. Buffered on TCLK. ACNET variable. FTP variable.	As in Table 2
Lattice and coupling measurements	TBT	Prot coal. Prot uncoal.	TBT buffer.	As in Table 2

Calibration and Maintenance

A calibration system that maintains the specifications needs to be designed. The resolution specification only needs to be self maintained for the time specified by the long-term stability specification. Beyond that, some calibration procedure is assumed. The system should also have enough built in maintenance procedures to realize an internal system malfunction and to diagnose the problem to the level of any replaceable component.

User Interface Requirements

Part of the BPM system will be a user interface to control the operation of the BPM system. It is expected that the interface will be used by only one person at a time, but there are no requirements to enforce the single user option with software.

The user interface will be used to control and setup measurements by the BPM system including the tasks of:

- Selecting the Proton/Pbar mode of operation
- Setting the Arm and Trigger settings for automated measurements.
- Number of turns to select in the Flash mode.
- Enable system tests and calibration measurements.

Applications Programs

Making use of the BPM system for Tevatron operations and accelerator physics is a vital part of this project. Therefore attention must be given to the applications programs which use the BPM system and their requirements documented. Later versions of this document (or a separate document) will be needed to complete the requirements of the application software. For this version of the document we list the application programs that are currently used by the Tevatron to control the BPM system or collect orbit or BLM data and require that the functionality of these programs be maintained as part of the BPM upgrade.

BPM Control Parameters (T37)

This program is used to monitor and set parameters of the BPMs. An example is the mode of the BPMs which can be set to BATCH mode for uncoalesced beam or BUNCH mode for coalesced beam. This page is also used to set the number of averages for a SNAPSHOT frame. The BPM system microprocessors can also be rebooted from this application program.

BPM/BLM Tests (T38)

This program is used to monitor and test aspects of the BPM electronics. These include tests of the RF modules, tests of cable continuity, and power supply.

BPM/BLM Plots (T39)

This program is used to collect orbit position data from the BPM system and display the results numerically and graphically. Orbit data can be archived and retrieved from a database. Other application programs can also retrieve data saved by T39 by using a set of CLIB BPM routines.

BLM Data and Control (T40)

This program gives the status of the BLM monitors and is used to display the BLM loss monitor readings.

BPM Beam Diagnostic (T41)

This program is used during shot setup to check BPMs. The response of the BPMs to a series of "1-bumps" is compared to the estimated response and BPMs which are out of tolerance are flagged as faulty.

Tevatron TBT Analysis (T42)

This program is used to plot the TBT readings from individual BPMs. It is used to look for transverse injection oscillations or longitudinal energy or RF phases mismatches at injection.

BLM Time Plot (T44)

This program is used to plot a history of a BLM response over the last few seconds before an abort. This is useful when trying to diagnose the location of beam loss, and the nature of the beam loss – whether the loss was gradual or sudden for instance.

Tev Orbit Closure (T117)

This program collects FLASH and DISPLAY data during Tevatron injections (both proton injection and reverse proton injection) for injection closure. The program calculates corrections for the injection line trim magnates and sends the corrections to hardware.

Tev Orbit Program (C50) (aka TOP)

TOP is a major program in the suite of Tevatron applications. This program uses orbit data to calculate corrections needed for smoothing the orbit.

Sequenced Data Acquisition (SDA)

Used during shot setup to collect orbits from the BPM system. This way the orbits for every shot setup are archived and can be used for future reference, analysis, or orbit smoothing.

Sequencer (C48)

The sequencer is the main program controlling the Tevatron during the shot setup process or during machine studies. The program has a sequence of commands which control the timing of Tevatron ramps, etc. There are several commands which affect and control the BPMs. For instance, switching from BATCH mode to BUNCH mode is done with a command directly from the sequencer.

Justification for the Requirements

There are six major functions that this BPM system must perform in order to justify an upgrade. Some of the functions are already part of the current BPM system, and some of the functions cannot be reliably performed by the current BPM system.

Tune Orbits – This function requires the best resolution and accuracy of the system over a large dynamic range. Injection orbits, orbits up the ramp, and flattop orbits are tested with a pilot bunch. Reverse injection for pbar orbits are also tested. It is very important that BPM readings for the pilot bunch can be carried over to 36 bunch readings within the specifications. The readings cannot be corrupted between the beam current of the pilot bunch, and the HEP current.

Injection Diagnostics – This function requires the best trigger and time stamp resolution. A flash of the first turn of injected beam is compared to a measured closed orbit or a previously saved reference orbit. Information from the injected betatron wave is used to tune the beam lines. Also, any more serious injection problems, such as beam not making a complete circulation, can be resolved by monitoring individual BPM intensity data on the first turn. These diagnostics require that the BPM system trigger precisely on the first turn, or any turn specified by the user. Synchronization between BPMs is critical.

Orbit Smoothing During HEP – This function requires the best resolution and long term stability. This resolution must not be corrupted by the pbars in the machine. Orbit smoothing will be performed during HEP to place the beam in its best orbit to minimize losses and maximize stability. Orbits from previous stores will be used as references, so it is important that the system not fall out of calibration from store to store.

Orbits Up the Ramp for Shots – This function is used to verify the orbits during shots that were tested originally by the pilot bunches. Accuracy and resolution are not as essential here as with other functions. The things that make this function challenging are the number of data points required over a short time period, the changing energy and orbits over a short time period, and pbar beam.

Lattice Function Measurements – This function requires very good resolution and linearity. The specified position resolution of the proton signals is a factor of 10 better than the resolution of the current BPMs. This will improve the determination of lattice parameters from a precision of 10% to a precision of 1%. Even with the improvement of resolution, we still detect about a factor 10 less precise than the magnet supplies can regulate.

Measurement of Antiprotons – The main motivation for measuring the antiproton orbits is that it may become important for understanding the Tevatron as it is pushed towards higher luminosity. It is also believed that solving the problem of measuring proton orbit positions in the presence of antiprotons will require instrumentation of the upstream end of the stripline pickups. Therefore, the same effort that is needed to measure protons can be used to measure the antiprotons.

Turn By Turn Measurement – Valuable information on the lattice parameters and transverse coupling in the Tevatron can be determined by analyzing turn by turn orbit positions. The requirements for the upgrades include a single turn measurement for injection tune up, so collecting many turns sequentially is not expected to be a difficulty.

Beam Loss Monitor Requirements

The present Tevatron Beam-Loss Monitor (BLM) system is considered to have satisfactory functionality by its users.[1] Given this situation, the requirements for the BLM part of the BLM/BPM Tevatron upgrade are:

a) Any upgrade or replacement of part of the BLM system shall provide all the present functionality of the present system. (The Tevatron department may identify some obsolete features.) Key features include the dynamic range which is 4 decades, the capability to check the integrity of the hardware, the flexibility to mask out individual detectors for specific situations, and the large amount of application software to control and monitor the BLM system and display its data.

b) Any change in the way the BLM system communicates with the systems it serves (for example the way it provides data to ACNET, the signals it generates to abort the beam) must be agreed to by the people responsible for the systems served.

c) There shall be a functioning Tevatron Beam Loss Monitoring system for operations at all times except perhaps for unavoidable interruptions due to installation of the new Tevatron Beam Position Monitoring System. While there are some features which could be added to the present system and there are some motivations to replace twenty-year old electronics with modern components, the major consideration in any proposed replacement should be to ensure that a BLM system is available at any time that it is needed.

d) The long-term system requirement is that any proposal consider the next 6 years of Tevatron operation. In particular, a proposal to leave part of the present system as is should either state that this part of the system will stay as is for the next 6 years or give a schedule for a replacement project. This may lead to a staged project where the Multibus functionality is replaced directly while leaving the BLM chassis as is.

A general description of the system is provided here for reference:

The Tevatron Beam Loss Monitor System serves the following functions.

a) to provide a signal to abort the beam in the Tevatron when the losses become unacceptable and threaten a quench. The signal must be provided both in case of

[1] ***For the record, additions to the system have been requested and include: 1) an application to store and compare BLM loss profiles in a manner similar to BPM profiles and 2) a programmable front-end capability to abort the beam on slow losses that would allow aborts at lower levels of slow loss than the present integrator time constant allows.***

a sudden loss and in the case of a continuous loss - see the system description for how this is handled in the present system.

b) to provide a diagnostic history showing the location of losses that may have caused a quench and the local/ring wide pattern of losses for 1 second before the quench.

c) to provide loss information to allow aperture scans and other studies to proceed without quenching the Tevatron and to allow accurate determination of apertures. This includes the ability to plot the loss information of each BLM using the fast time plot (FTP) facilities of the Beams Division control system.

The present BLM system has 4 parts:

1) The ion-chambers which provide a current when traversed by charged particles - these are the loss detectors. These have been extensively studied and recently chosen by RHIC. It is strongly suggested that these detectors continue to be the primary loss monitors.

2) The BLM chassis which in the Tevatron contains:

    a) up to 12 daughter cards with integrators and log amplifiers..the integration time is 1/16 second. This is set by measurements of the losses the Tevatron magnets can tolerate. Per an early memo from R. Shafer, these losses are 50 joules in a fast loss or a continuous loss of 800 joules/sec; The log amplifiers give a dynamic range of 4 orders of magnitude where an abort is triggered at magnitude about 3.3.
    b) alarm and abort generation logic.
    c) abort signal generation.
    d) alarm and abort threshold setting logic.
    e) control logic to mask out specific channels
    f) registers with alarm and abort status
    g) controllable HV supplied to ion chambers
    h) self-checking features including continuity and voltage checks.
    i) multiplexing ADC for the output of the log amplifiers;
    j) External Device Buss (EDB) communication protocol with a control computer.
    k) the provision to send two channels of raw signals after the integrator stage to MADC's

3) The Multibus CPU which sets up the BLM chassis, reads the ADC and other data, stores a history buffer, talks EDB and communicates with the accelerator control system. The CPU controls the BLM chassis on events. The reference document from Al Baumbaugh is Beams Doc 764.

4) A set of console applications to control and diagnose the BLM system and display BLM data, both house by house data and ring-wide data in a convenient way, particularly on an abort or quench.

Application pages include:

T37 BPM/BLM Multibus control/reset
T39 Ring wide BPM and BLM display
T40 BLM Control and Display
T44 BLM Buffer display
T48 Tevatron Sequencer
C48 Tevatron Sequencer
T67 The abort display

There is a coupling between the Tevatron BPM and BLM system in that anytime the BPM system provides a snapshot, the current BLM data are also presented to ACNET. This feature is implemented in the Multibus CPU.

References

[1] Internal Fermilab Review of the Tevatron BPM Upgrade Requirements, June 4th, 2003. No report was published.

[2] Department of Energy Assessment of the Run II Luminosity Plan at the Fermilab Tevatron. July, 2003.

[3] The Run II Luminosity Upgrade at the Fermilab Tevatron. June 15th, 2003.